Searching for Compressed SUSY using Low pT Leptons with the ATLAS Detector

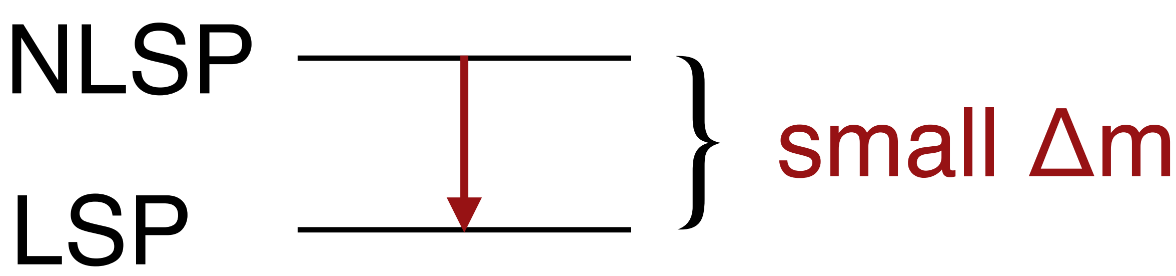
Joey Reichert

University of Pennsylvania
joey@cern.ch

July 31, 2017

Introduction

Compressed Spectrum:



If NLSP decays to LSP and e.g. an off-shell Z, expect low pT leptons!

- Signature we'll focus on: **2 low pT leptons**, **MET**, and **ISR jet**
- Soft leptons pose challenges such as:
  - triggering (standard dilepton triggers start at pT > 14 GeV)

    ➡ use MET trigger instead!
  - particle reconstruction / identification
  - background estimation

Signal Models

Two main signal models considered:

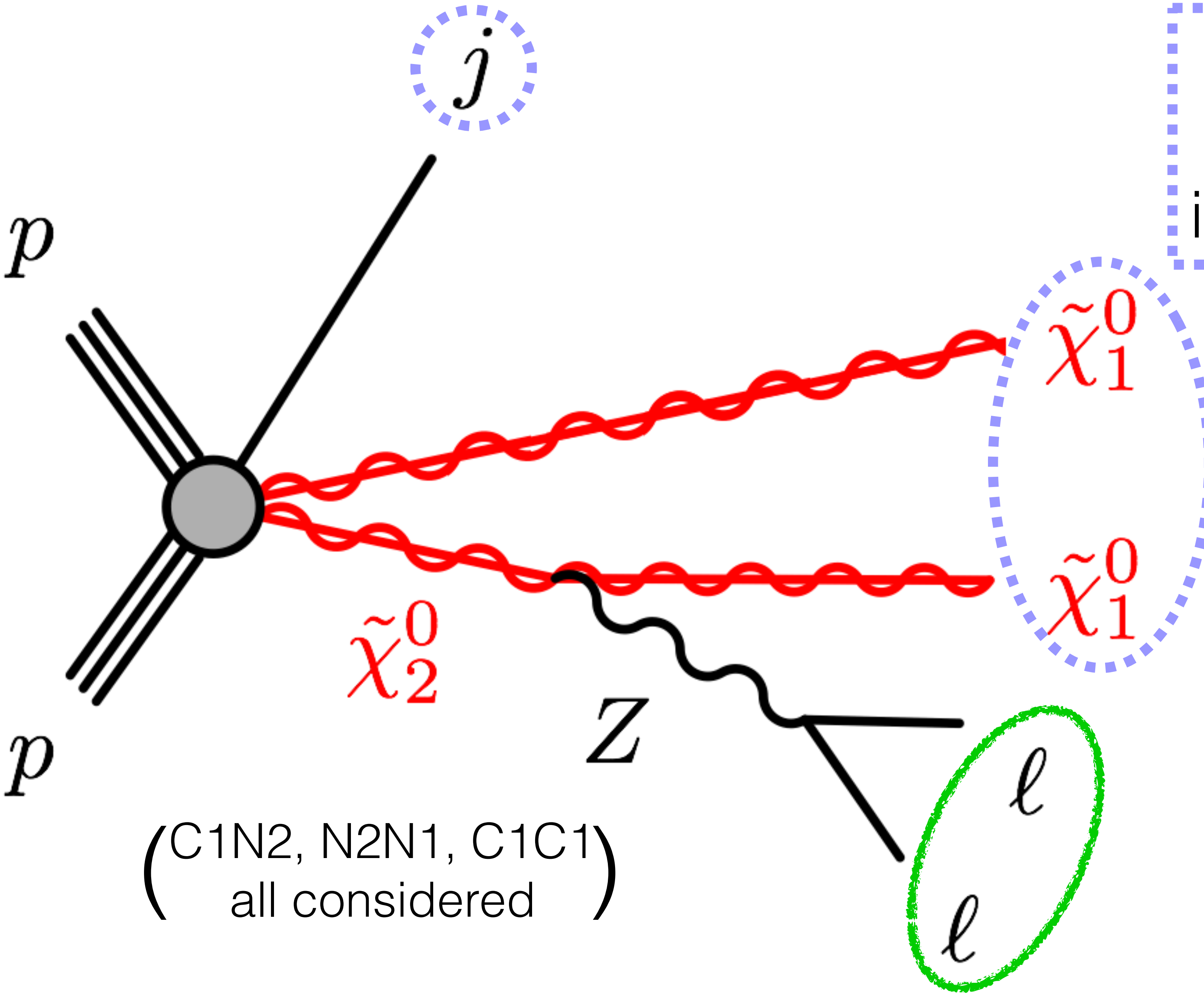
1) Higgsino LSP

- In many natural SUSY scenarios, a light Higgsino expected since its mass parameter μ should live at the weak scale
- LSP which is pure or mostly Higgsino results in small Δm(LSP, NLSP)
  - ➡ Pure Higgsino: O(MeV) splittings
  - ➡ Predominantly Higgsino mixings: O(1-10 GeV) splittings

2) Compressed sleptons

- Can provide answers to experimental observations including dark matter relic density and the muon g-2 anomaly

Higgsino Analysis Strategy



(C1N2, N2N1, C1C1 all considered)

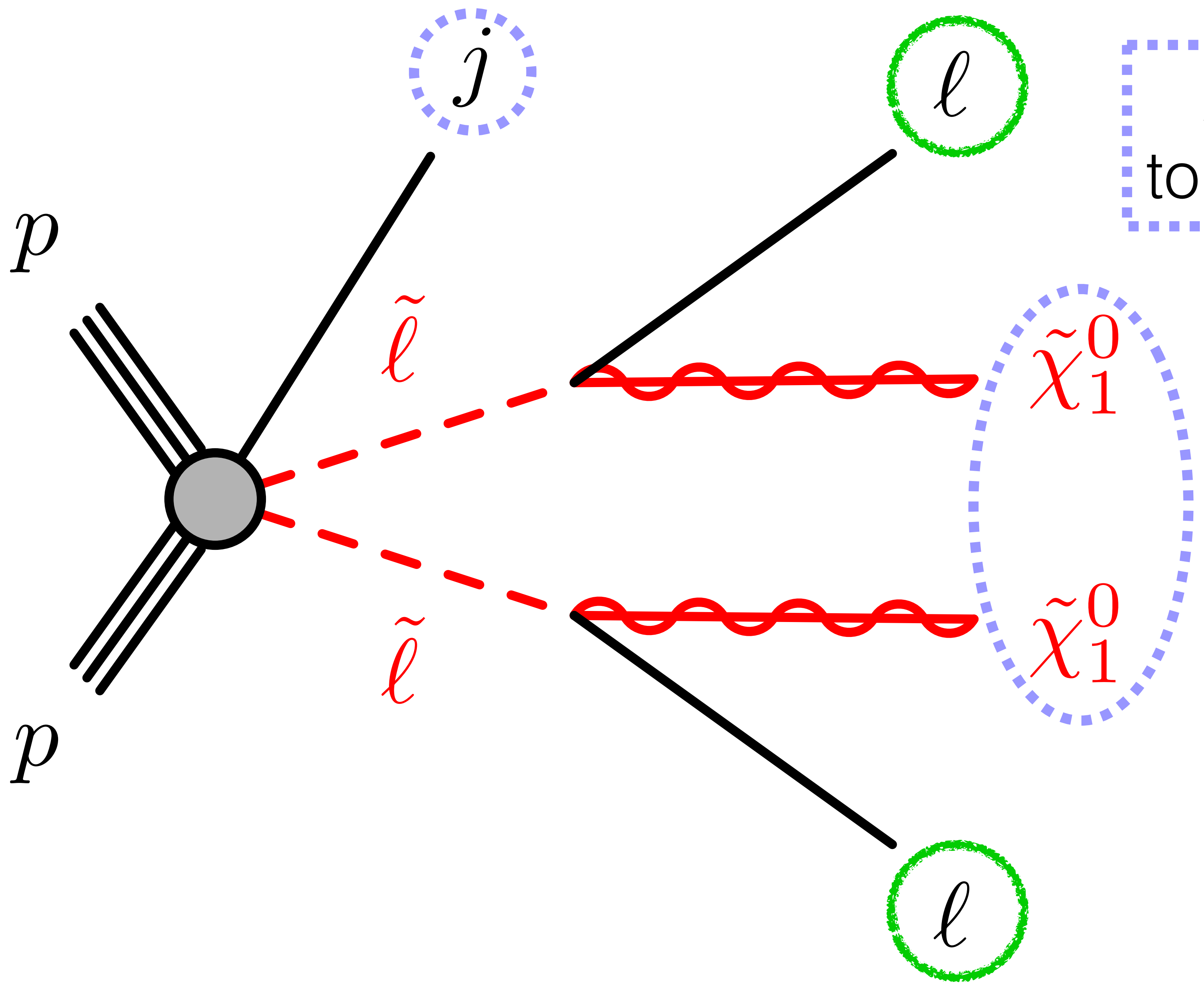
Rely on an ISR jet to boost the LSPs enough for the inclusive MET trigger to fire.

Even with a boost, lepton pT is driven by Δm(N2, N1).

Low pT leptons are key to the search!

Primary observable: kinematic endpoint in the mll distribution at Δm(N2, N1)

Compressed Slepton Analysis Strategy



As for Higgsinos, use ISR topology with the MET trigger

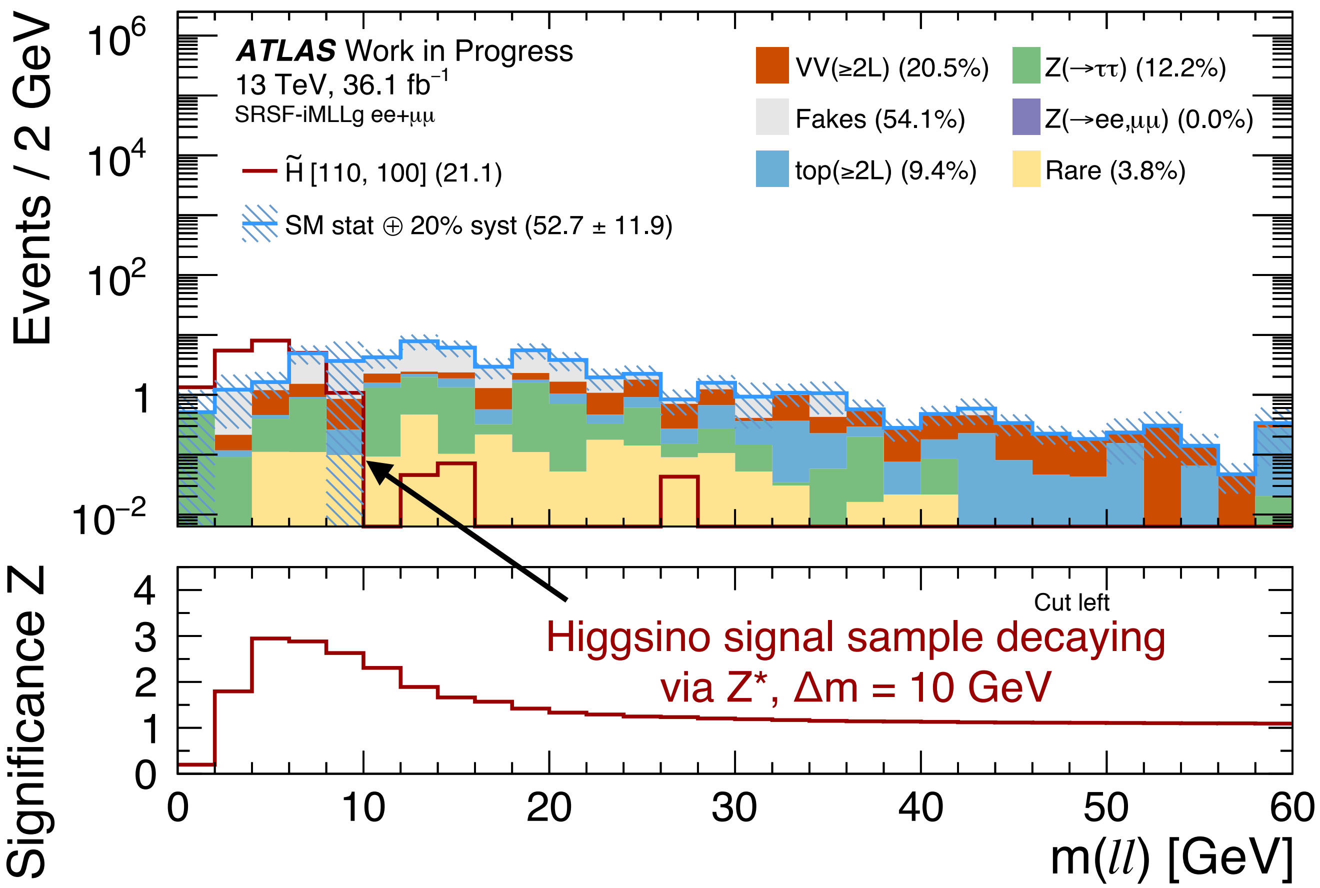
Small Δm(slepton, N1), so low pT leptons key here as well

Primary observable: kinematic endpoint in the m_{T2} distribution at the slepton mass

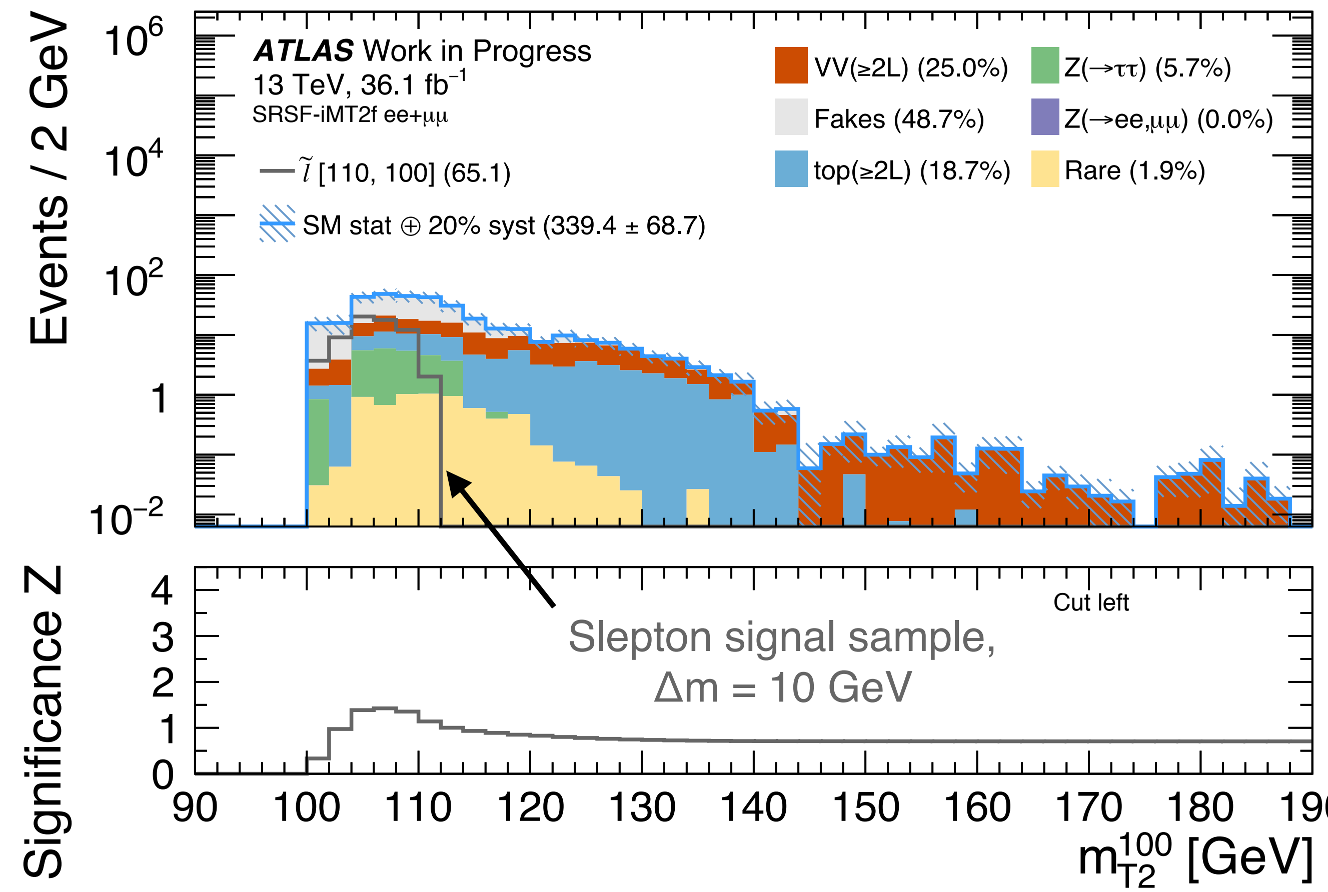
m_{T2}: analogue of m_T for pair produced particles which each decay to visible + invisible

Primary Discriminating Variables

Higgsino SR



Slepton SR



Higgsinos: kinematic endpoint at mll = Δm(N2, N1)
Sleptons: kinematic endpoint at m_{T2} = m(slepton)

These are our primary observables—but note that they are dependent on the masses and mass splittings

Common Event Selection

Variable	Requirement
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 200 GeV
Leading jet $p_{\mathrm{T}}(j_1)$	> 100 GeV
$\left\lvert\Delta\phi(j_1, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})\right\rvert$	> 2.0
$\min\left\lvert\Delta\phi(\text{all jets}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})\right\rvert$	> 0.4
$N_{\mathrm{b-jet}}^{20}$, 85% WP	Exactly zero
N_{leptons}	Exactly two well-identified leptons
Lepton charge and flavour	$e^{\pm}e^{\mp}$ or $\mu^{\pm}\mu^{\mp}$
Leading electron (muon) $p_{\mathrm{T}}^{\ell_1}$	$> 5(5)$ GeV
Subleading electron (muon) $p_{\mathrm{T}}^{\ell_2}$	$> 4.5(4)$ GeV
$m_{\tau\tau}$	Veto [0, 160] GeV
$m_{\ell\ell}$	$> 1, < 60$ GeV, veto [3, 3.2] GeV
$\Delta R_{\ell\ell}$	> 0.05

LSP recoils off of jet

Reduce low (and high) mass resonances

Additional SR Event Selection

Higgsino SR

Variable	Requirement
$E_{\mathrm{T}}^{\mathrm{miss}}/H_{\mathrm{T}}^{\mathrm{leptons}}$	$> \mathrm{Max}\,(5.0, 15 - 2 \cdot m_{\ell\ell}/\ \mathrm{GeV})$
$\Delta R_{\ell\ell}$	< 2.0
$m_T^{\ell_1}$	< 70 GeV

Suppress backgrounds with high pT leptons

Leptons from Higgsino decay tend to be nearby

Reduce W+jets (fake leptons)

Slepton SR

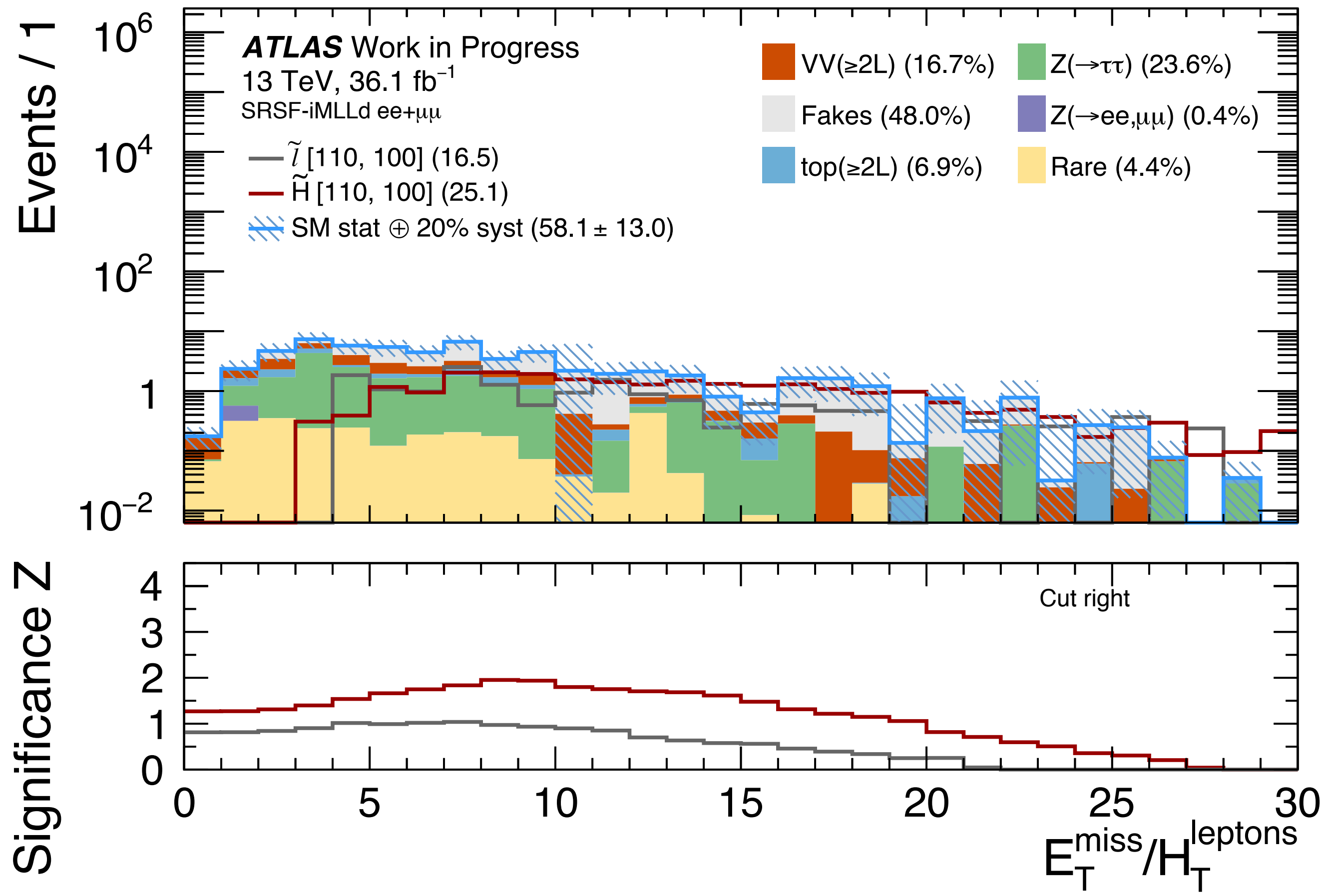
Variable	Requirement
$E_{\mathrm{T}}^{\mathrm{miss}}/H_{\mathrm{T}}^{\mathrm{leptons}}$	$> \mathrm{Max}\left(3.0, 15 - 2 \cdot \underbrace{\left[m_{\mathrm{T2}}^{100}/\ \mathrm{GeV} - 100\right]}_{\text{Δm(slepton, LSP), using an m(LSP) = 100 GeV assumption}}\right)$

Same as above, but for the m_{T2} distribution.

Events which pass the Higgsino or Slepton SR requirements are then used in shape fits of the mll or m_{T2} variables, respectively.

Example Discriminating Variables

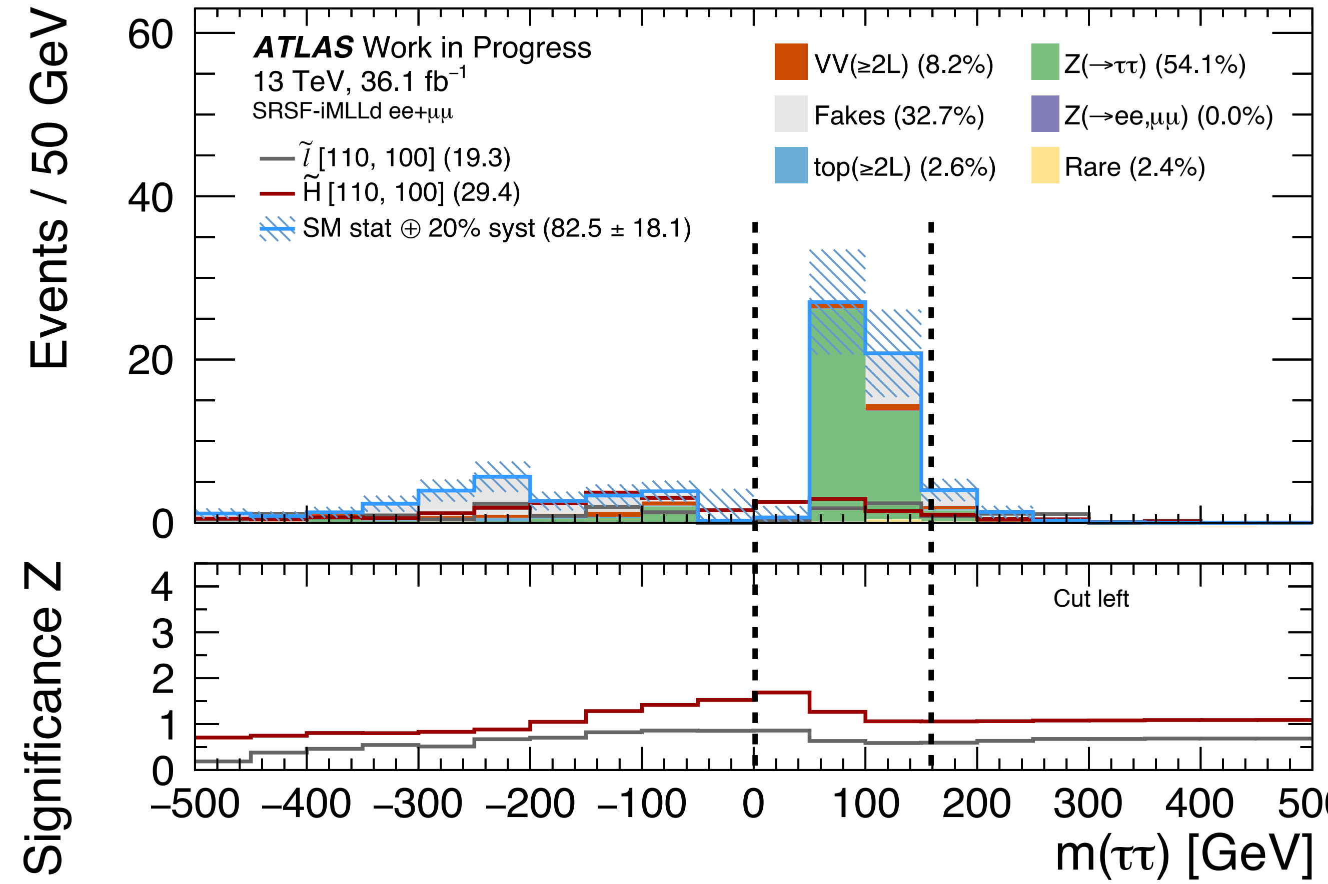
MET/H_T^{Lep}



Ratio of MET and the lepton pT scalar sum.

Ensures that the MET comes from the jet recoil, rather than hard leptons

$m_{\tau\tau}$



Use MET and the visible leptons to reconstruct tau kinematics, and obtain a proxy for the di-tau mass

Background Sources

Background process	Origin in signal region	Estimation strategy
$t\bar{t}$, tW (2ℓ)	Irreducible, b-jet fails identification	CR using b-tagging
$Z(\to \tau\tau)$+jets	Irreducible fully leptonic taus	CR using $m_{\tau\tau}$
$Z(\to ee, \mu\mu)$+jets	Instrumental $E_{\mathrm{T}}^{\mathrm{miss}}$	Monte Carlo
Low mass Drell-Yan	Instrumental $E_{\mathrm{T}}^{\mathrm{miss}}$	Monte Carlo, data-driven cross-check
Fakes (W+jets, $VV(1\ell)$)	Jet fakes second lepton	Fake factor, same sign VR
VV	Irreducible dileptonic and missed 3rd lepton	Monte Carlo, VR using $E_{\mathrm{T}}^{\mathrm{miss}}/H_{\mathrm{T}}^{\mathrm{leptons}}$
Other rare processes	Irreducible leptonic decays	Monte Carlo

Target these backgrounds using CRs, VRs, data-driven fake estimation, and the MC (for smaller backgrounds).

CR and VR Definitions

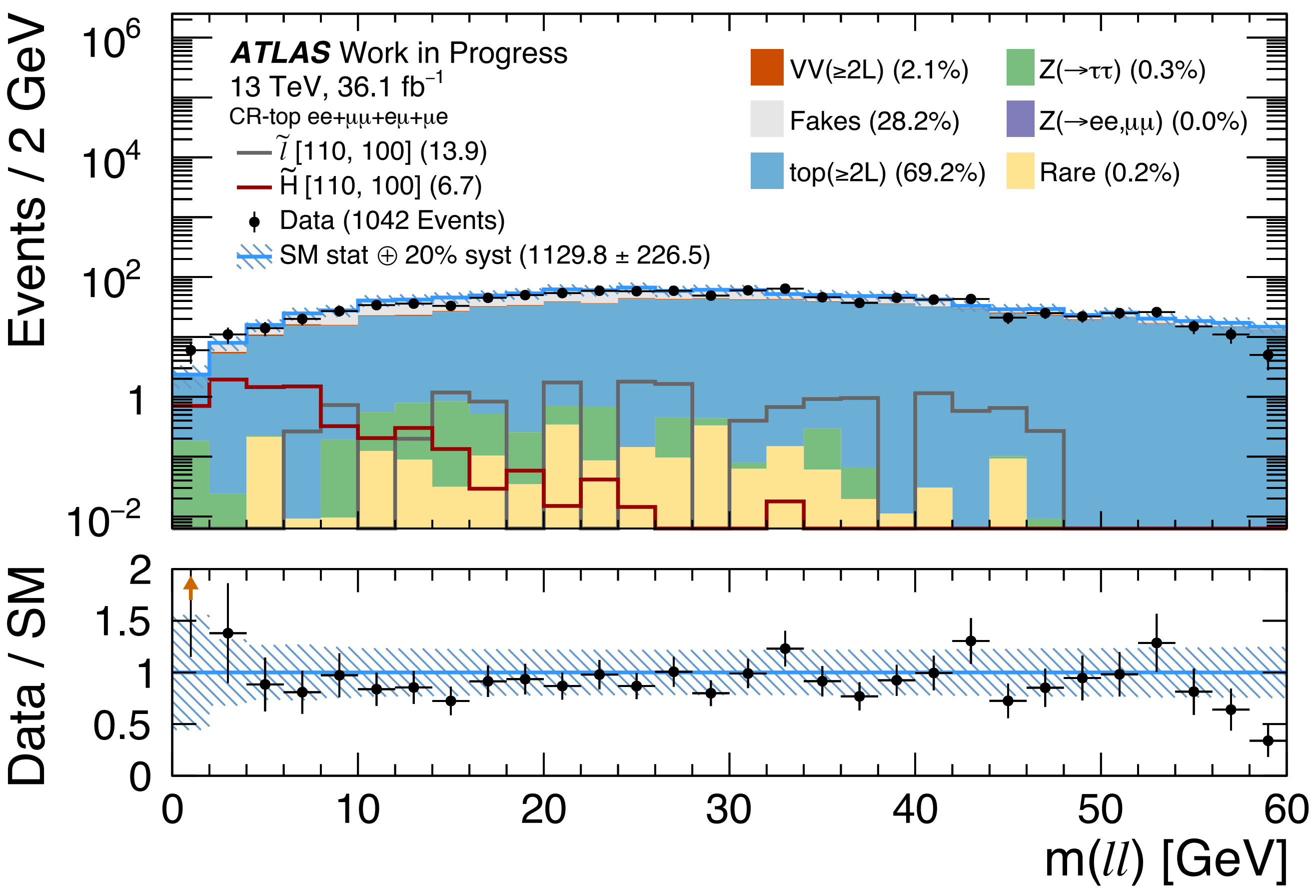
CRs and VRs defined are identical to the common event selection except for the quantities noted.

Also use eμ events to enhance CR statistics.

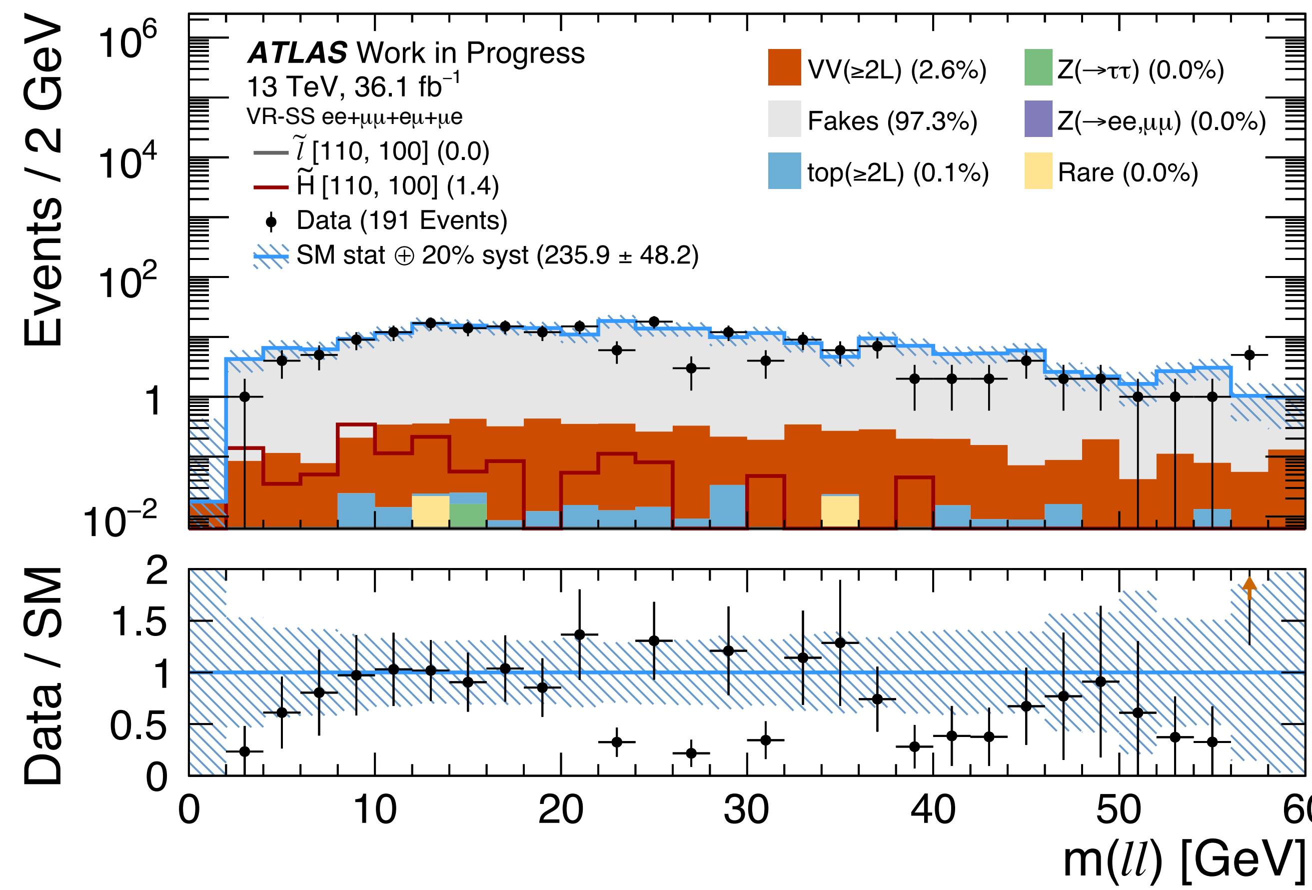
Region	SR orthogonality	Additional requirements	Flavour
CR-top	$N_{\text{b-jet}}^{20} \geq 1$	$E_{\mathrm{T}}^{\mathrm{miss}}/H_{\mathrm{T}}^{\mathrm{leptons}} > 5$	$ee + \mu\mu + e\mu + \mu e$
CR-tau	$m_{\tau\tau} \in [60, 120]$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}}/H_{\mathrm{T}}^{\mathrm{leptons}} \in [4, 8]$	$ee + \mu\mu + e\mu + \mu e$
VR-VV	$E_{\mathrm{T}}^{\mathrm{miss}}/H_{\mathrm{T}}^{\mathrm{leptons}} < 3$	–	$ee + \mu\mu + e\mu + \mu e$
VR-SS	Same sign $\ell^{\pm}\ell^{\pm}$	$E_{\mathrm{T}}^{\mathrm{miss}}/H_{\mathrm{T}}^{\mathrm{leptons}} > 5$	$ee + \mu e, \mu\mu + e\mu$
VRDF-MLL	$e\mu + \mu e$	Higgsino SR Selection	$e\mu + \mu e$
VRDF-MT2	$e\mu + \mu e$	Slepton SR Selection	$e\mu + \mu e$

Example CR and VR

CR-top



VR-SS

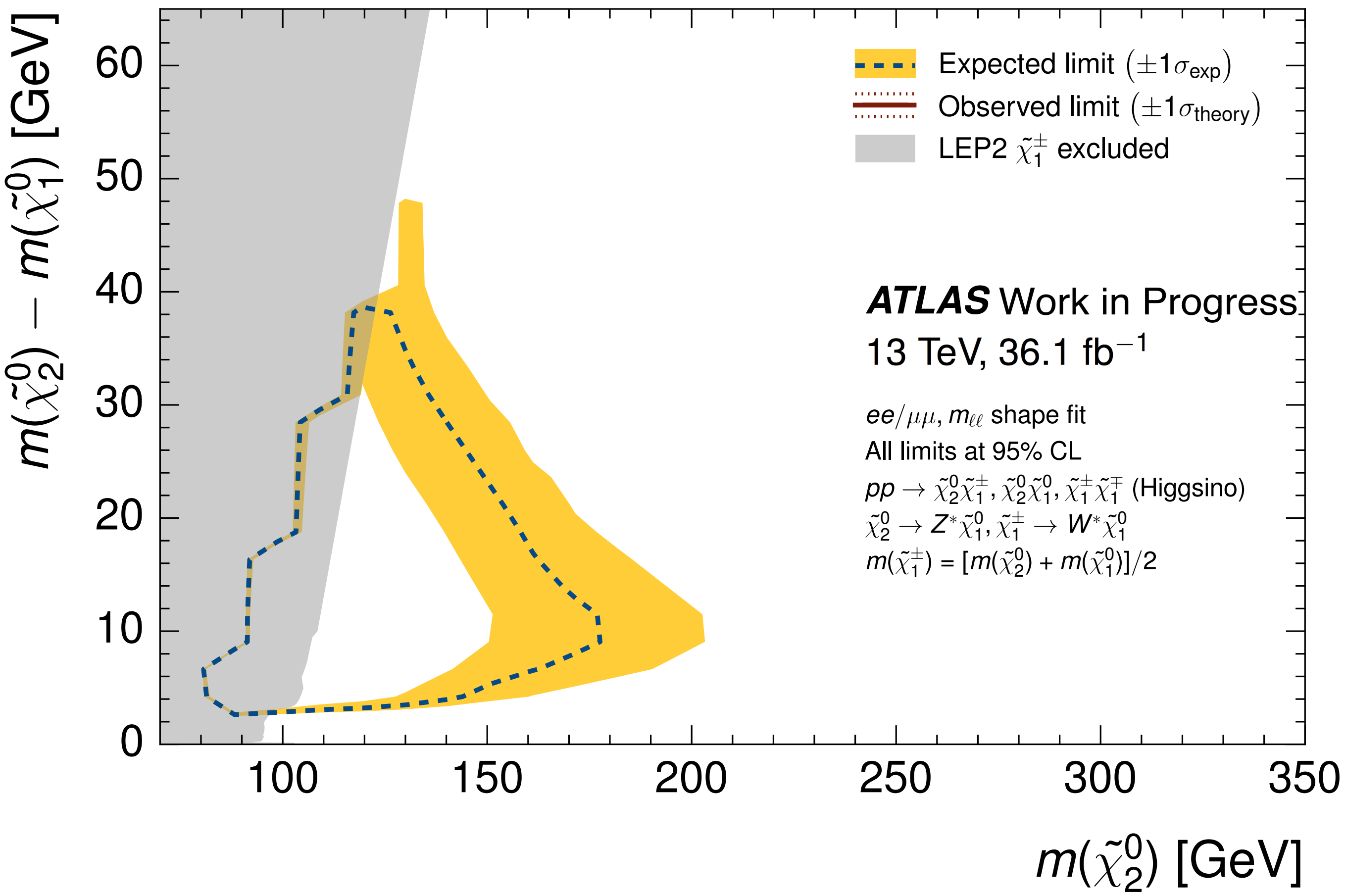


- CR-top (≥1 b-jet) used to derive ttbar normalization factors
- VR-SS is predominantly W+jets, and shows reasonable agreement between data and our fake lepton estimate

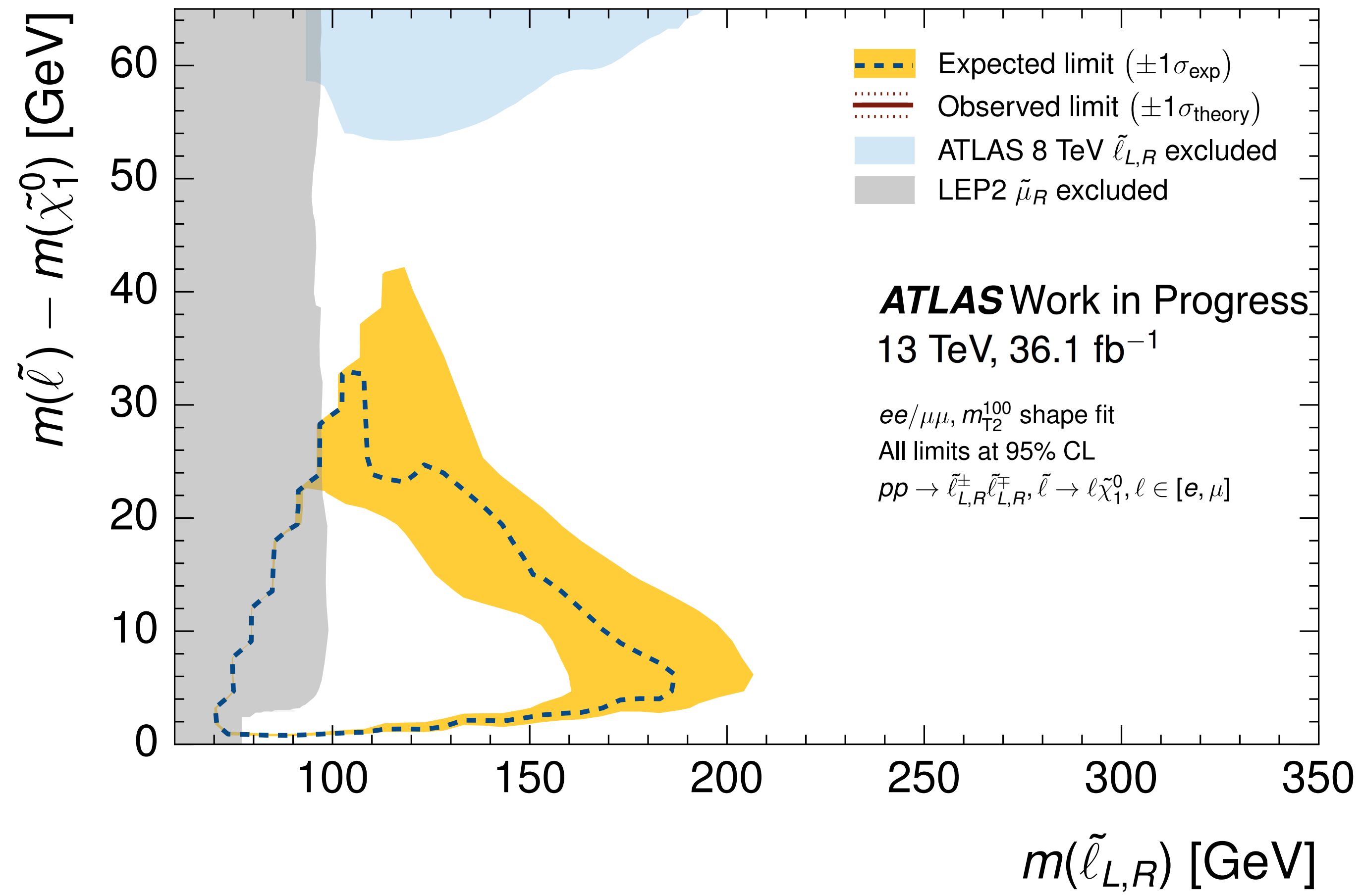
Disclaimer: assumes flat 20% systematic uncertainties, and some estimates are still being improved

Expected limits

Higgsino Limits



Slepton Limits



Improving upon the LEP limits!

- Higgsinos: expect to probe down to Δm = 3 GeV and up to m(N2) = 175 GeV
- Sleptons: expect to probe down to Δm = 1 GeV and up to m(slepton) = 185 GeV

LEPSUSYWG 01-03.1, 02-04.1, and 04-01.1

Summary

- Searching for compressed SUSY is well-motivated but nontrivial!
  - Background sources which are negligible for many other analyses are crucial here
  - Large fake lepton backgrounds which must be suppressed or estimated
- Electroweak production $\Rightarrow$ small cross-sections
  - Run 2 luminosity will help to cover this interesting phase space!

Backup

Higgsino mass splittings

Case 1: Heavy bino

$M_1 >> M_2 > \mu$

$$\left|m_{\chi_2^0}\right| - \left|m_{\chi_1^0}\right| \approx \frac{m_W^2\left(\pm|\mu|\, s_{2\beta} + M_2\right)}{\left(M_2^2 - |\mu|^2\right)}$$

Case 2: Heavy wino

$M_2 >> M_1 > \mu$

$$\left|m_{\chi_2^0}\right| - \left|m_{\chi_1^0}\right| \approx \frac{m_W^2 t_{\theta_W}^2\left(\pm|\mu|\, s_{2\beta} + M_1\right)}{\left(M_1^2 - |\mu|^2\right)}$$

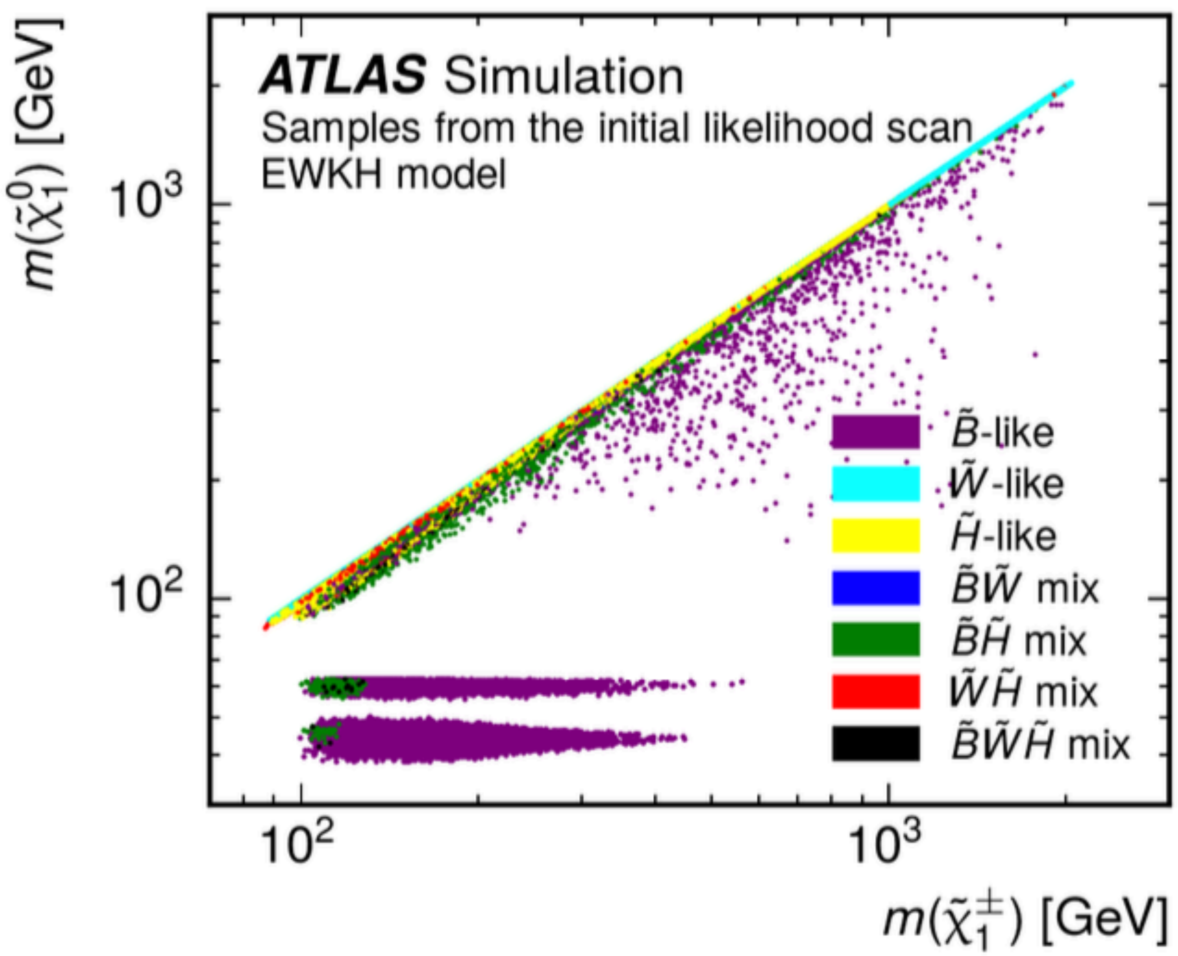
$$\Longrightarrow \quad \Delta m(N2, N1) \approx \frac{(m_W)^2}{\min(M_1, M_2)}$$

So if e.g. M_1 or M_2 is O(1-2 TeV), then $\Delta m \approx$ 3-6 GeV

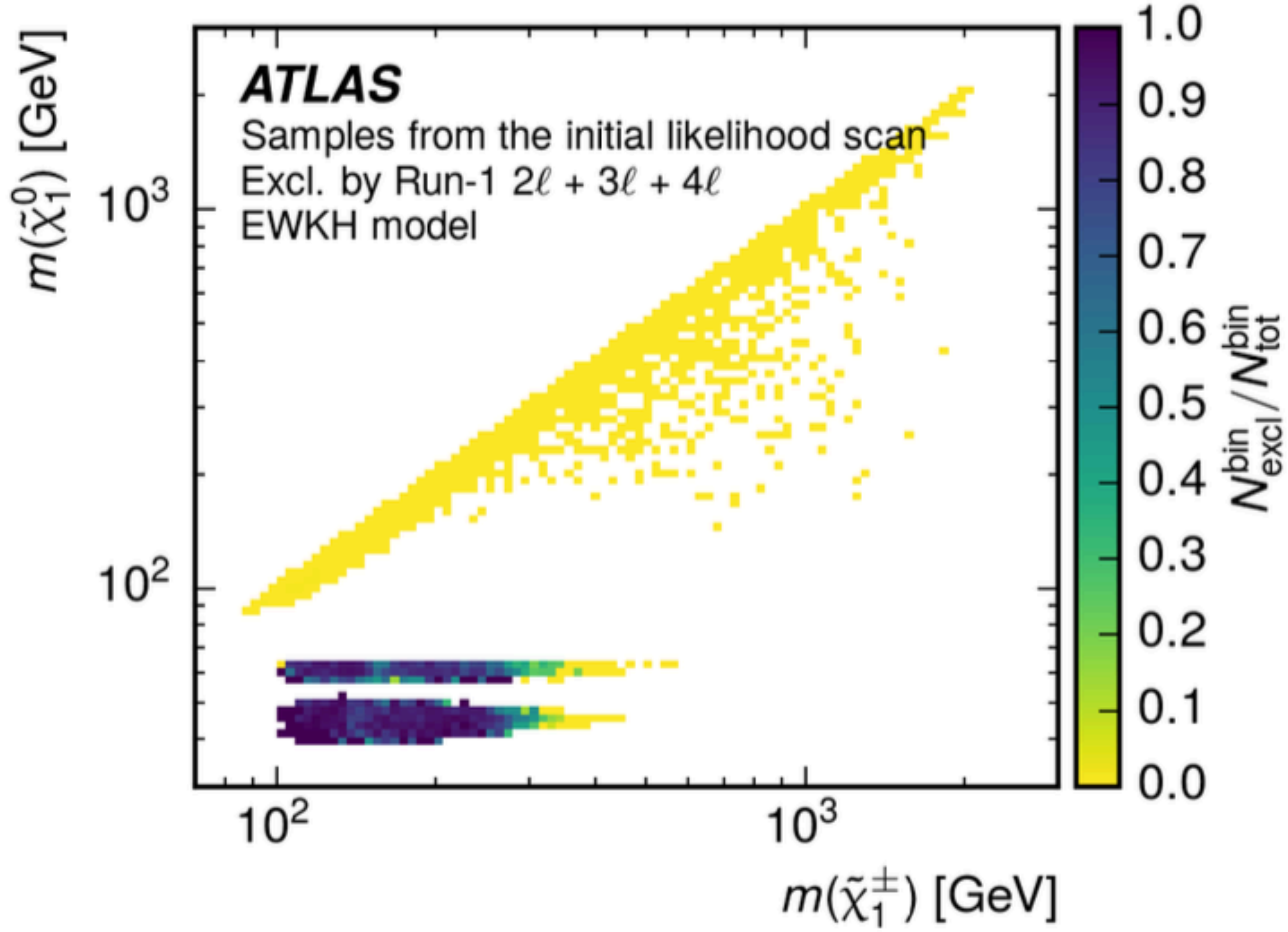
arXiv:1401.1235

Theoretical Motivation

5-parameter pMSSM scan from Run 1 DM Summary Paper



(a) Composition of lightest neutralino.

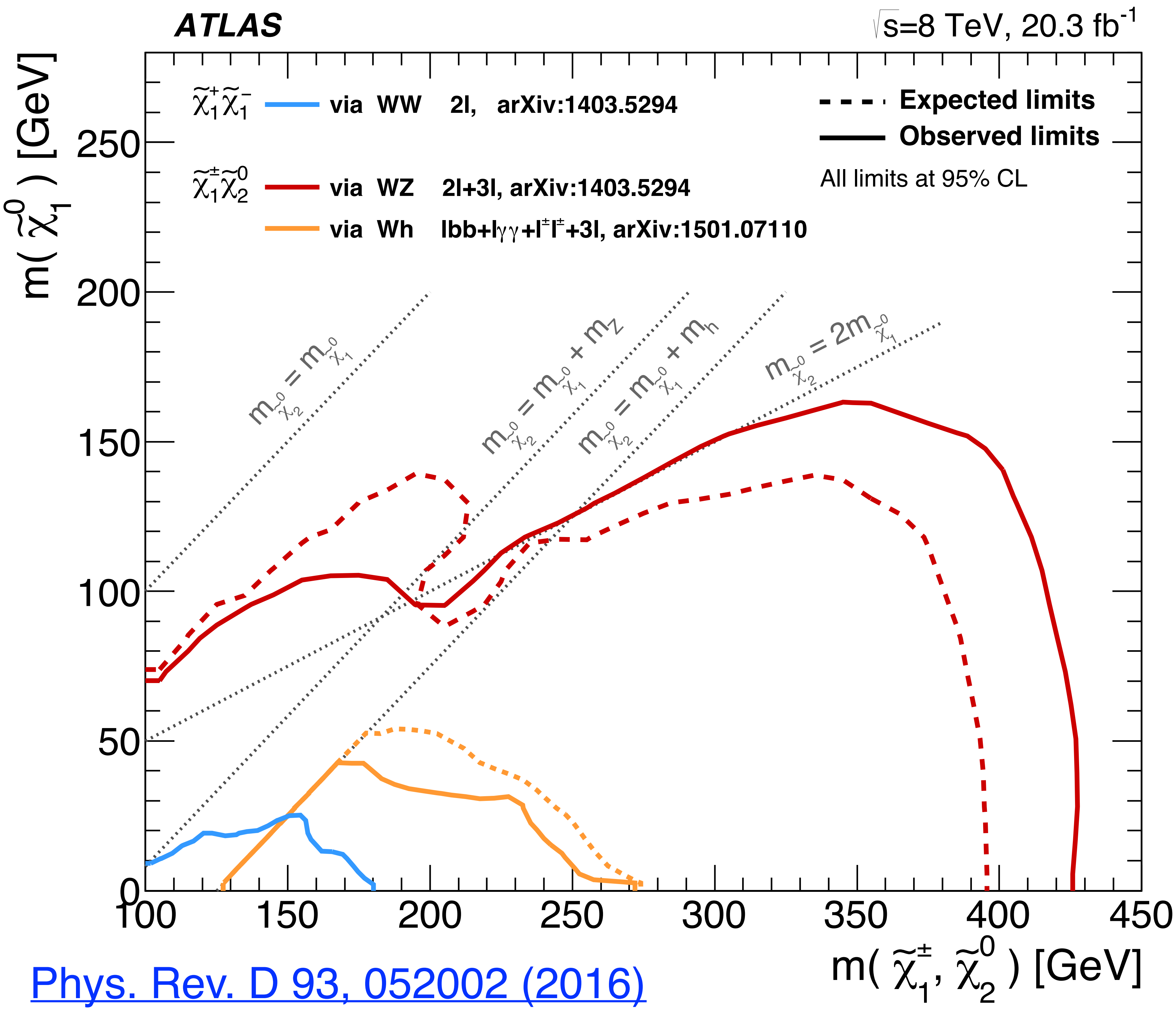


(b) Fraction of points excluded per bin from Run 1.

Higgsino LSPs tend to fall along the diagonal,
which has evaded searches so far

JHEP09 (2016) 175

Existing limits on EWK production



Run 1 ATLAS limits only probed down to Δm ≈ 50 GeV, but this also assumes Wino cross-sections, which are 2x-4x larger than for Higgsinos

[Phys. Rev. D 93, 052002 (2016)]

Signal Samples

- Generated using Madgraph at LO with up to two extra partons and showered with Pythia8
- Resummino at NLL+NLO used to compute the cross-sections

Specific for Higgsino samples:

- Madspin used to model the off-shell W*/Z* decays properly
- For e.g. a 120_100 grid point, the N2 is 120 GeV, N1 is 100 GeV, and C1 (for C1N2 events) is halfway between them

General Analysis Strategy

- Use a mix of data-driven techniques and MC for background estimation. For backgrounds with…
  - ➡ real MET and real leptons (e.g. WW), use MC
  - ➡ fake MET and real leptons (e.g. Drell-Yan), use data and MC
  - ➡ real MET and fake leptons (e.g. W+jets), use data

- Beyond mll and m_{T2}, use additional discriminating variables for control, validation, and signal regions
  - Perform shape fits in mll and m_{T2} for discovery/exclusion in several signal models
  - Also provide model-independent limits in inclusive and overlapping SRs for reinterpretation

Object Definitions

Property	Signal	Baseline
Electrons		
Kinematic	$\boxed{p_{\mathrm{T}} > 4.5\ \mathrm{GeV},}$ $\lvert\eta\rvert < 2.47$ (include crack)	$p_{\mathrm{T}} > 4.5\ \mathrm{GeV}$
Identification	TightLLH	VeryLooseLLH
Isolation	GradientLoose	–
Impact parameter	$\lvert d_0/\sigma(d_0)\rvert < 5$, $\lvert z_0 \sin\theta\rvert < 0.5$ mm	$\lvert z_0 \sin\theta\rvert < 0.5$ mm
Muons		
Kinematic	$\boxed{p_{\mathrm{T}} > 4\ \mathrm{GeV},}$ $\lvert\eta\rvert < 2.5$	$p_{\mathrm{T}} > 4\ \mathrm{GeV}$
Identification	Medium	Medium
Isolation	FixedCutTightTrackOnly	–
Impact parameter	$\lvert d_0/\sigma(d_0)\rvert < 3$ & $\lvert z_0 \sin\theta\rvert < 0.5$ mm	$\lvert z_0 \sin\theta\rvert < 0.5$ mm
Jets		
Kinematic	$p_{\mathrm{T}} > 30\ \mathrm{GeV}$, $\lvert\eta\rvert < 2.8$	$p_{\mathrm{T}} > 20\ \mathrm{GeV}$, $\lvert\eta\rvert < 4.5$
Clustering	Anti-k_t $R = 0.4$ EMTopo	Anti-k_t $R = 0.4$ EMTopo
Pileup mitigation	JVT Medium for $p_{\mathrm{T}} < 60\ \mathrm{GeV}$, $\lvert\eta\rvert < 2.4$	–
b-tagging	$p_{\mathrm{T}} > 20\ \mathrm{GeV}$, $\lvert\eta\rvert < 2.5$, MV2c10 FixedCutBeff 85%	–

Using the softest leptons available to us!

Variable definitions

- m_{T2}: analogue of m_T, used to bound the mass on pair produced particles decaying to a visible and invisible component. Defined as:

$$m_{\mathrm{T2}}^2\left(p_{\ell_1}, p_{\ell_2}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}; \chi\right) = \min_{\mathbf{q}_{\mathrm{T}}}\left(\max\left[m_{\mathrm{T}}^2\left(\mathbf{p}_{\mathrm{T}}^{\ell_1}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}, \chi\right), m_{\mathrm{T}}^2\left(\mathbf{p}_{\mathrm{T}}^{\ell_1}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}} - \mathbf{q}_{\mathrm{T}}, \chi\right)\right]\right)$$

where $\mathbf{q} = \mathbf{p}_{\mathrm{T}}^{\chi,1} + \mathbf{p}_{\mathrm{T}}^{\chi,2}$

Variable definitions

- $m_{\tau\tau}$: designed to reconstruct the di-tau invariant mass based on the visible lepton momenta and the MET. Defined as:

$$m_{\tau\tau}\left(p_{\ell_1}, p_{\ell_2}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}\right) = \begin{cases} \sqrt{m_{\tau\tau}^2} & m_{\tau\tau}^2 \geq 0, \\ -\sqrt{\left|m_{\tau\tau}^2\right|} & m_{\tau\tau}^2 < 0. \end{cases}$$

with $$m_{\tau\tau}^2 = (p_{\tau_1} + p_{\tau_2})^2 \simeq 2p_{\ell_1} \cdot p_{\ell_2}(1+\xi_1)(1+\xi_2)$$

and $$\begin{pmatrix} \xi_1 \\ \xi_2 \end{pmatrix} = \frac{1}{p_x^{\ell_1} p_y^{\ell_2} - p_x^{\ell_2} p_y^{\ell_1}} \begin{pmatrix} p_x^{\mathrm{miss}} p_y^{\ell_2} - p_x^{\ell_2} p_y^{\mathrm{miss}} \\ p_y^{\mathrm{miss}} p_x^{\ell_1} - p_x^{\mathrm{miss}} p_y^{\ell_1} \end{pmatrix}$$

Fake Factor Method

Fake factor = $\frac{N_{ID}}{N_{AntiID}}$, as measured in a fake-dominated region

- Numerator: analysis signal lepton ID
- Denominator: fake enriched selection disjoint from the numerator
- Binned in lepton flavor and pT (in principle could bin in η too)

Fake estimate obtained by applying FF to CR identical to SR but with an antiID lepton in place of one of the signal leptons

- Formally, this is mathematically treated as:

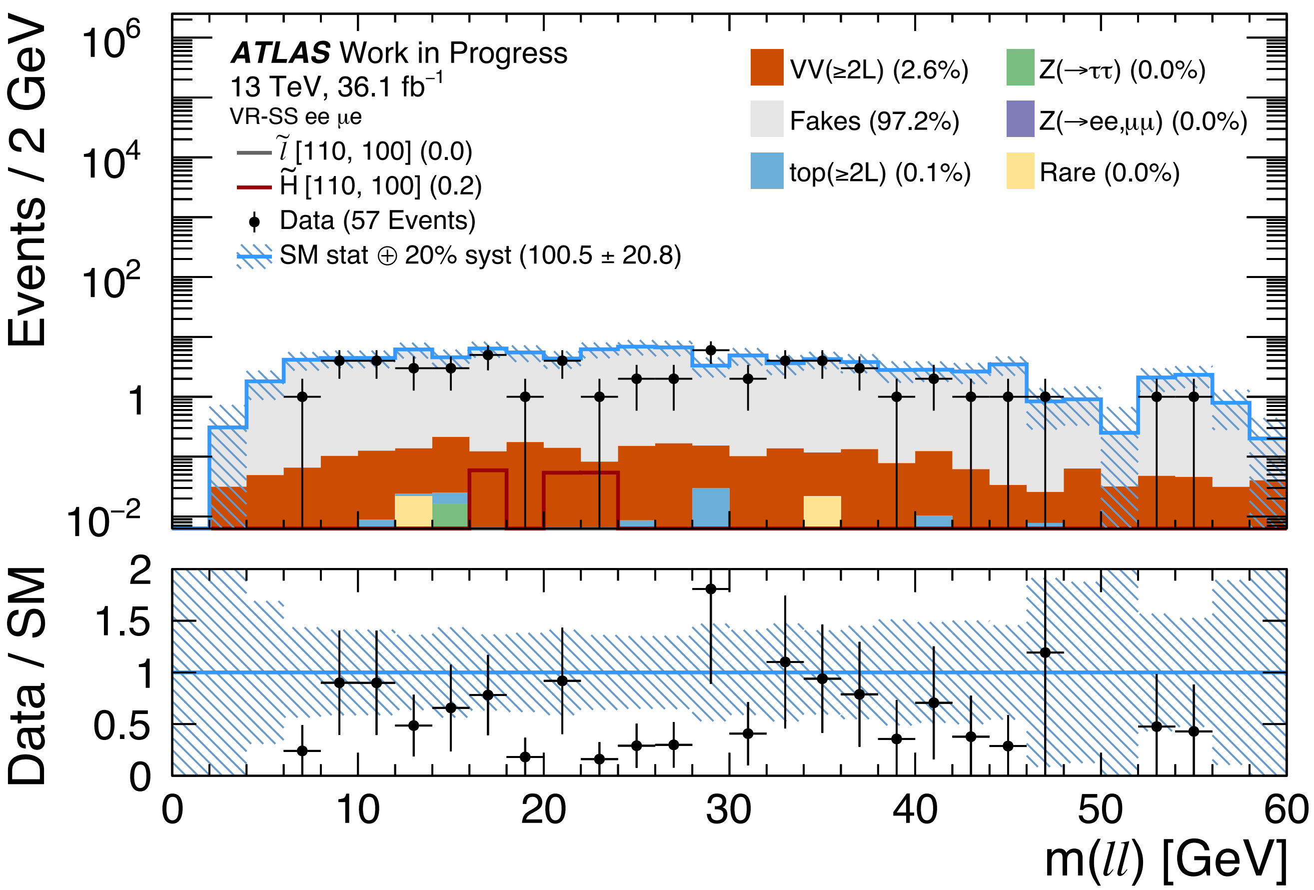
T = "tight" or ID lepton
L = "loose" or antiID lepton

$$N_{TT} - N_{TT}^{RR} = \left[N_{LT} - N_{LT}^{RR}\right] F_1 + \left[N_{TL} - N_{TL}^{RR}\right] F_2 - \left[N_{LL} - N_{LL}^{RR}\right] F_1 F_2$$

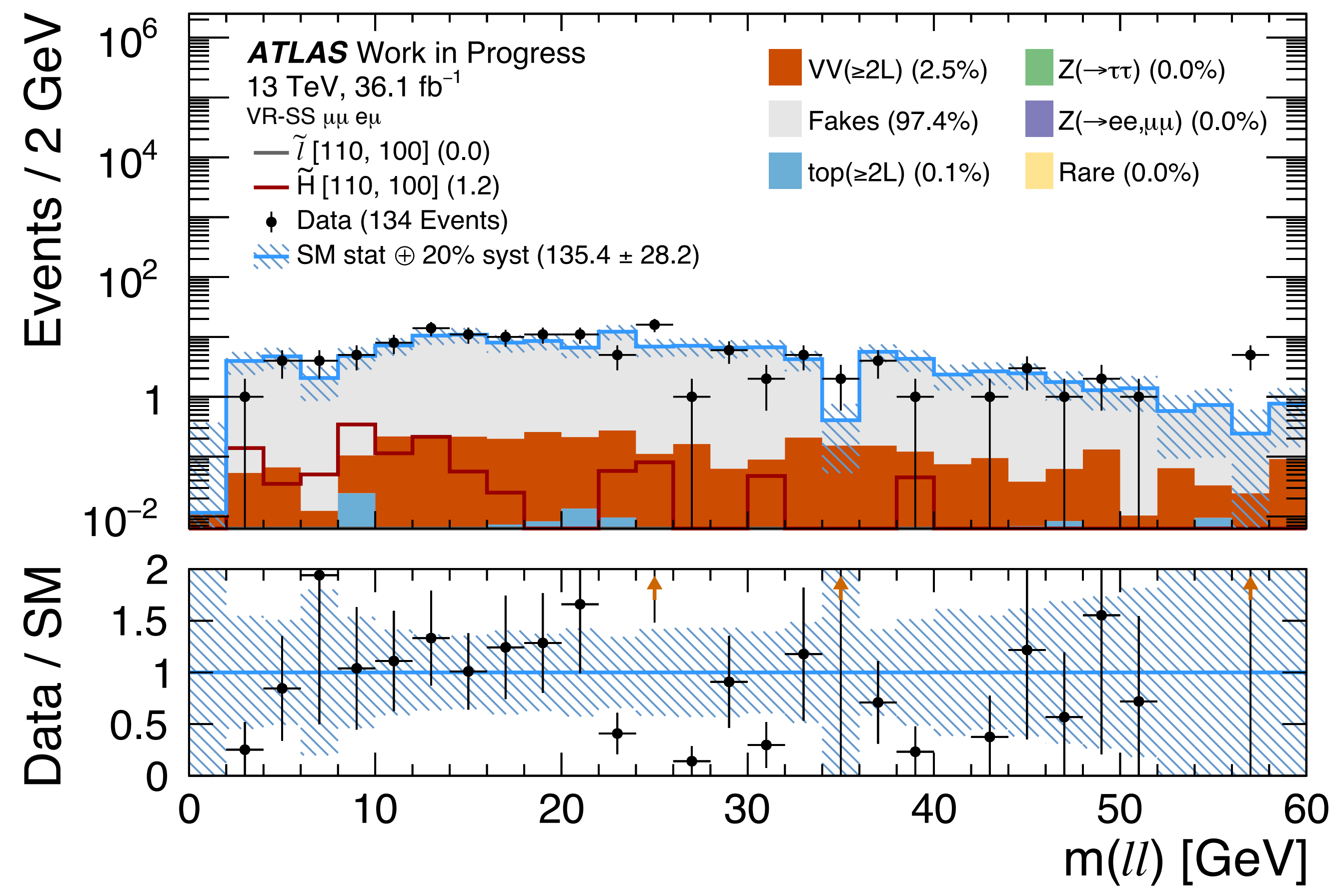
where "RR" refers to events with two real prompt leptons, which must be removed using the MC.

VR-SS for separate channels

Electron channel



Muon channel



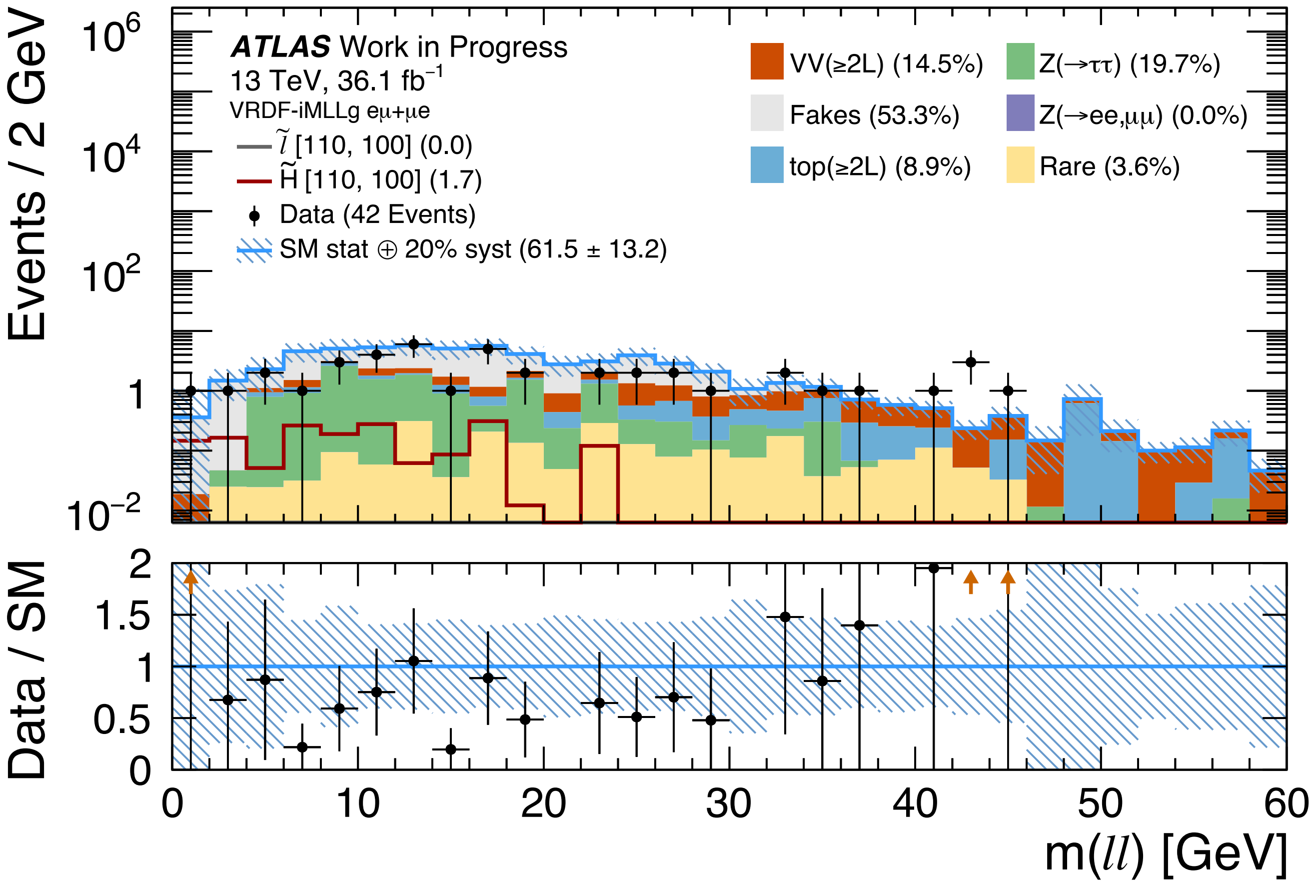
Reasonable agreement in the separate flavor channels for VR-SS.

Since the subleading lepton tends to be the fake, the eμ and μe events can be included here for validating the fake lepton estimate.

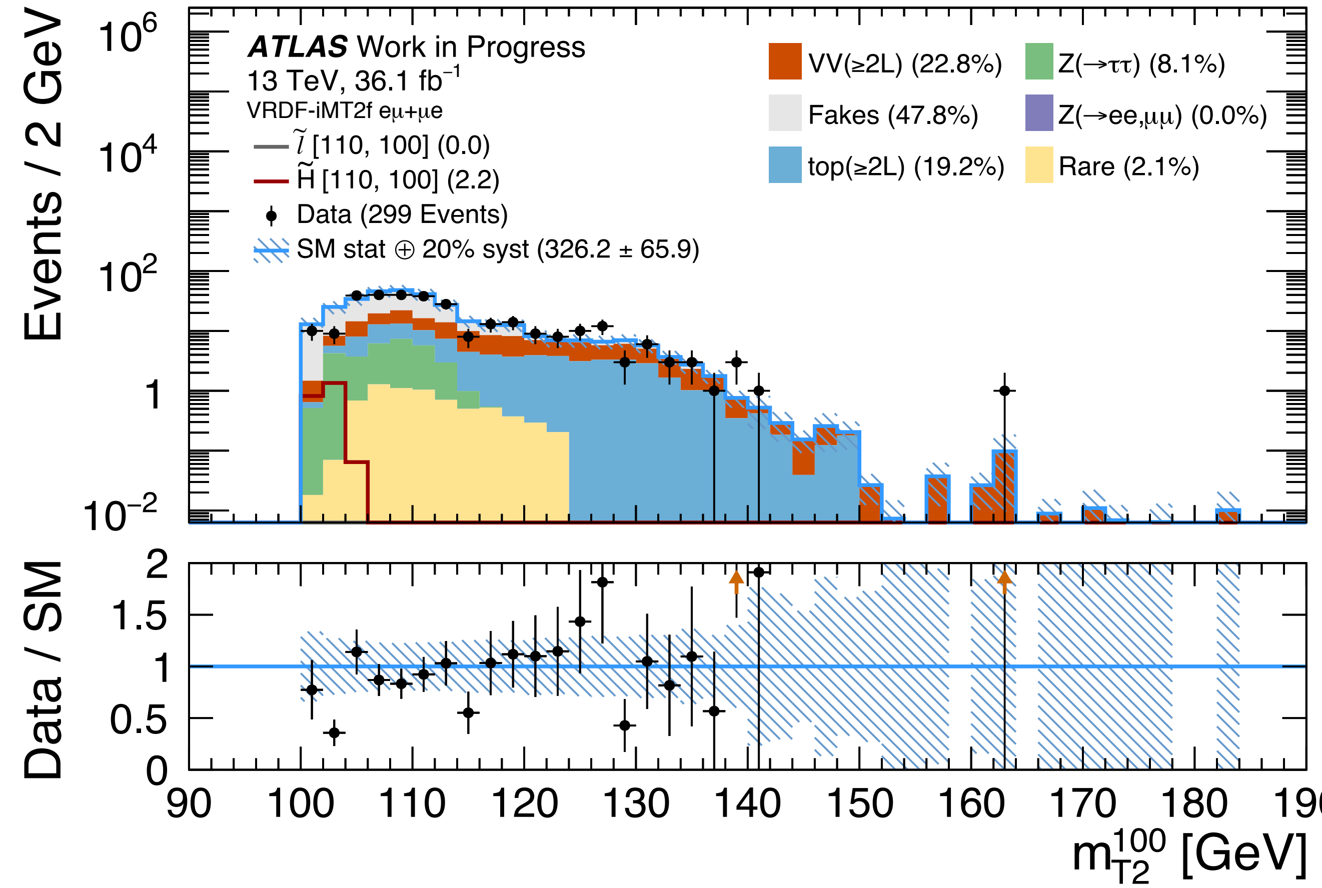
Disclaimer: assumes flat 20% systematic uncertainties, and some estimates are still being improved

eμ VRs

Higgsino DF VR



Slepton DF VR

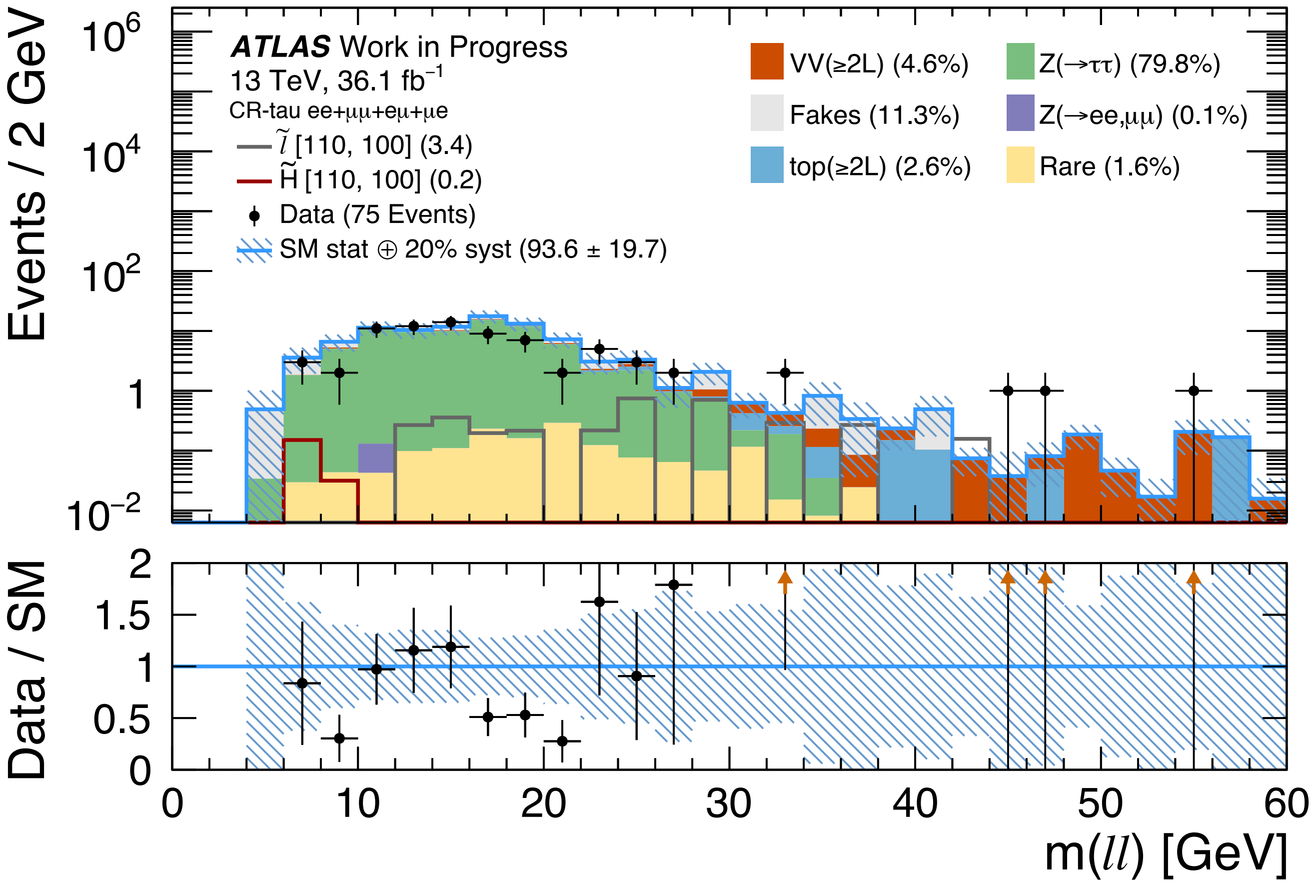


Reasonable agreement in the different-flavor validation regions

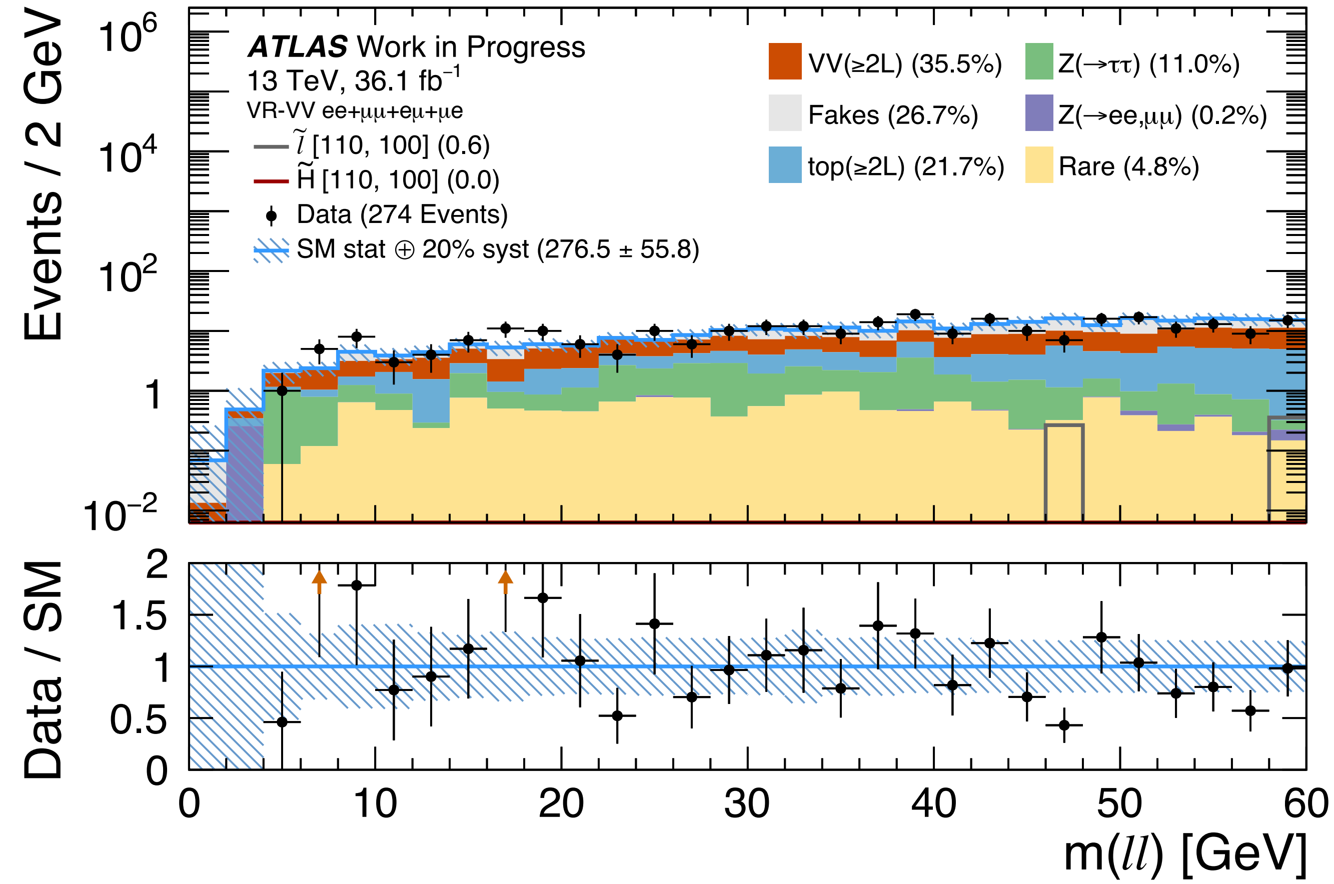
Disclaimer: assumes flat 20% systematic uncertainties, and some estimates are still being improved

CR-tau and VR-VV

CR-tau



VR-VV

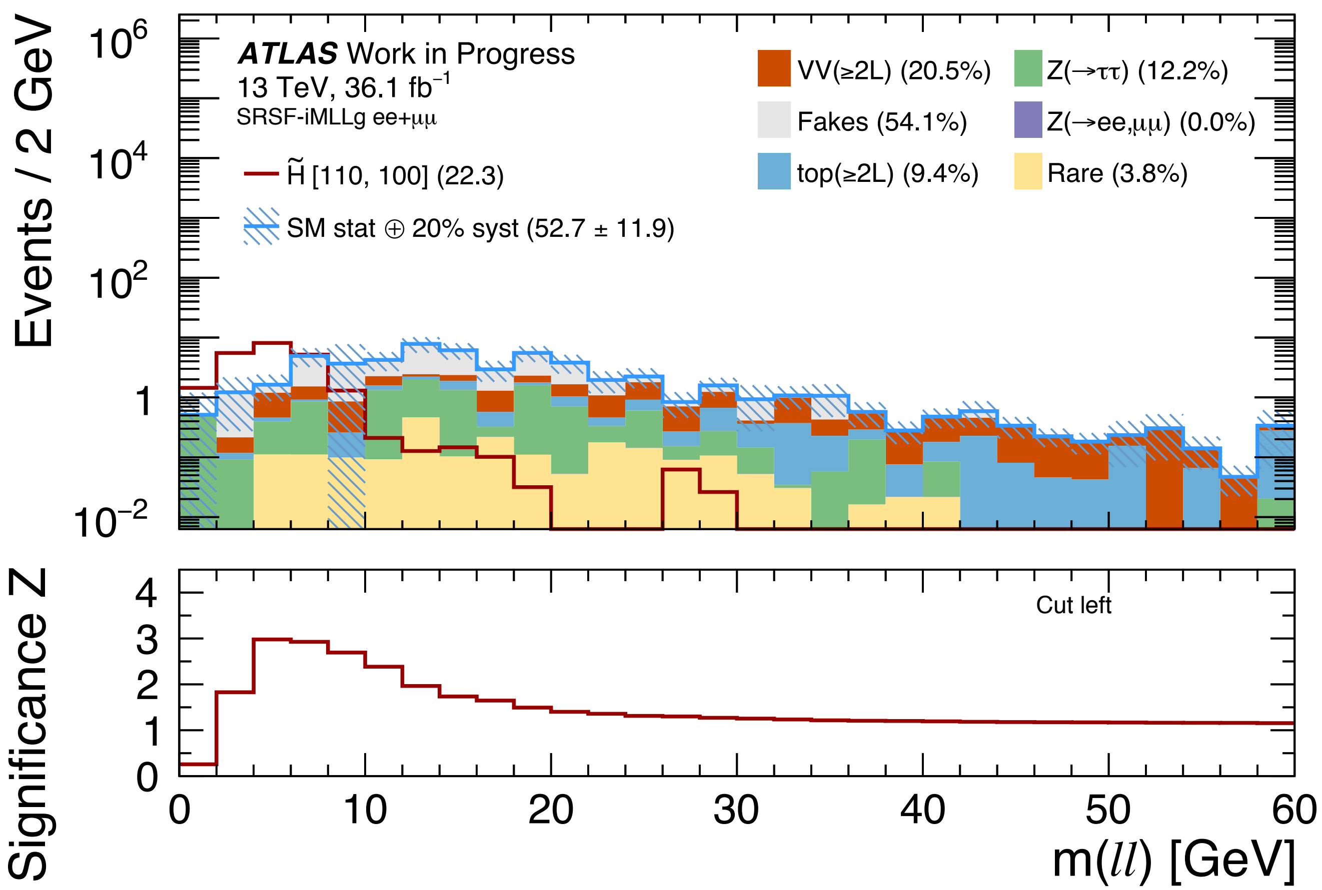


CR-tau used to determine a $Z \rightarrow \tau\tau$ normalization factor, while VR-VV used to test the VV modeling.

Disclaimer: assumes flat 20% systematic uncertainties, and some estimates are still being improved

Inclusive Higgsino SR, including C1C1

Higgsino SR

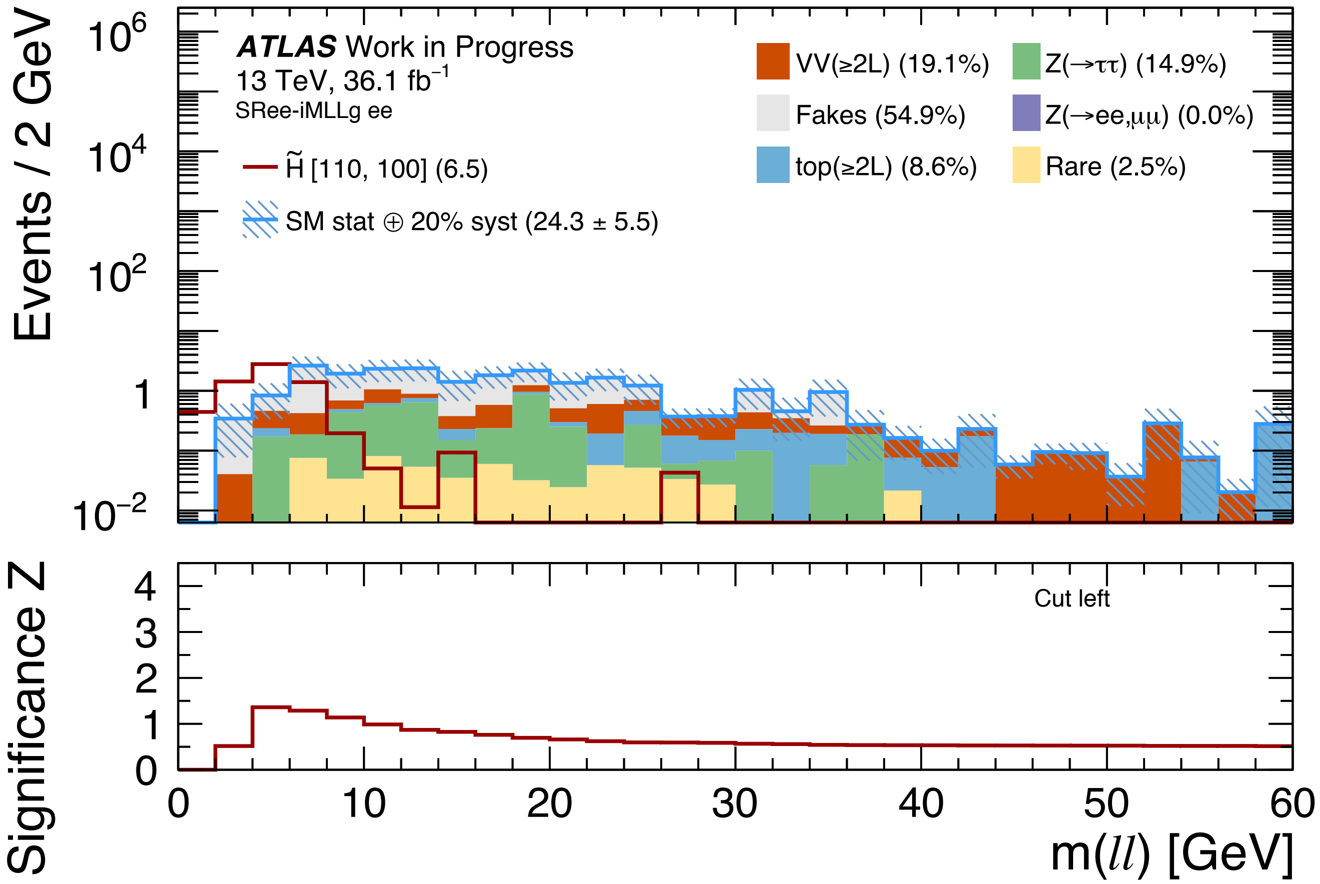


Unlike slide 6, this also includes the C1C1→W*W* decays, which do not contribute to the endpoint at mll = Δm(N2, N1).

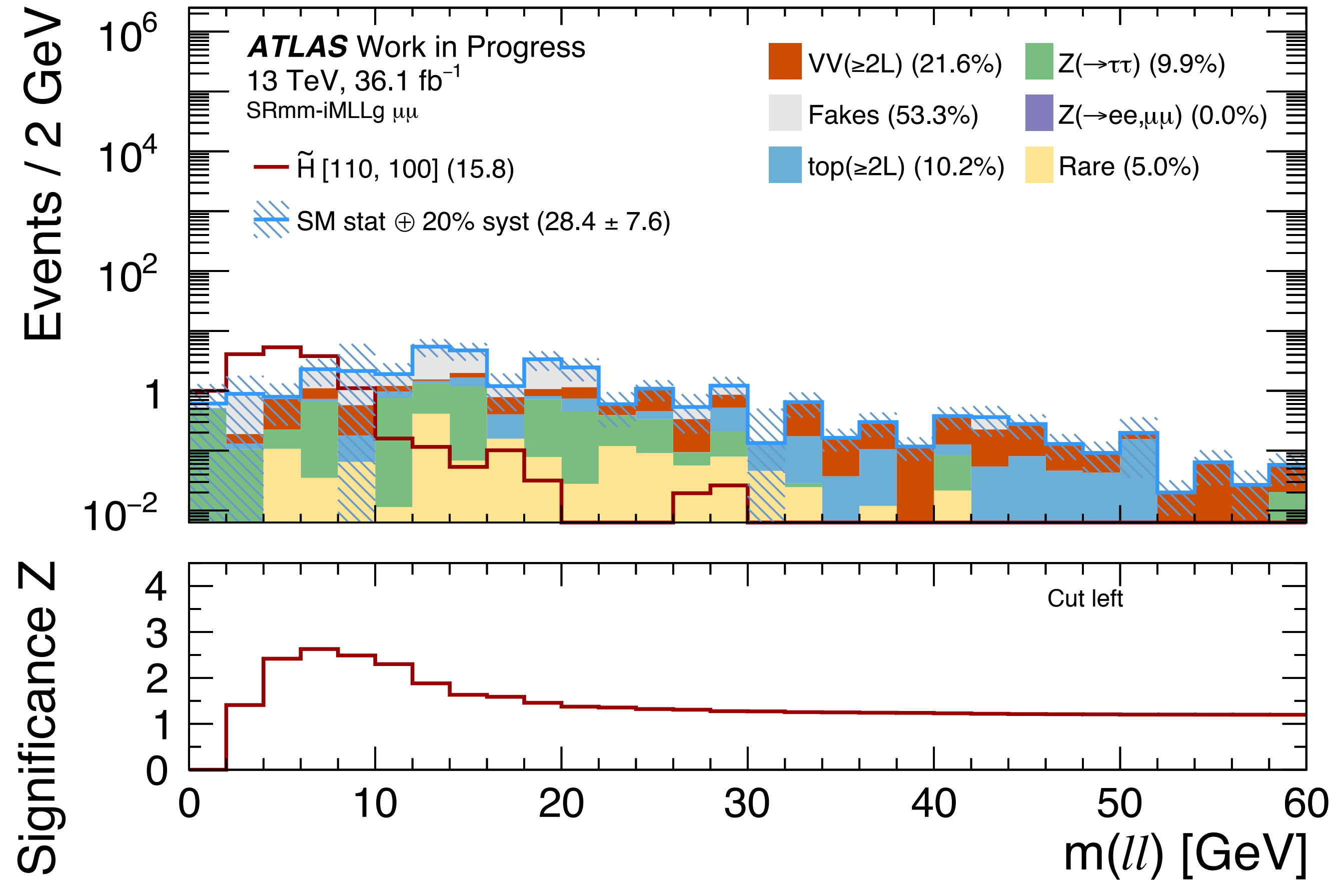
Only contributes 1.2 more signal events for this particular Δm.

Higgsino SR for ee vs. μμ

ee channel

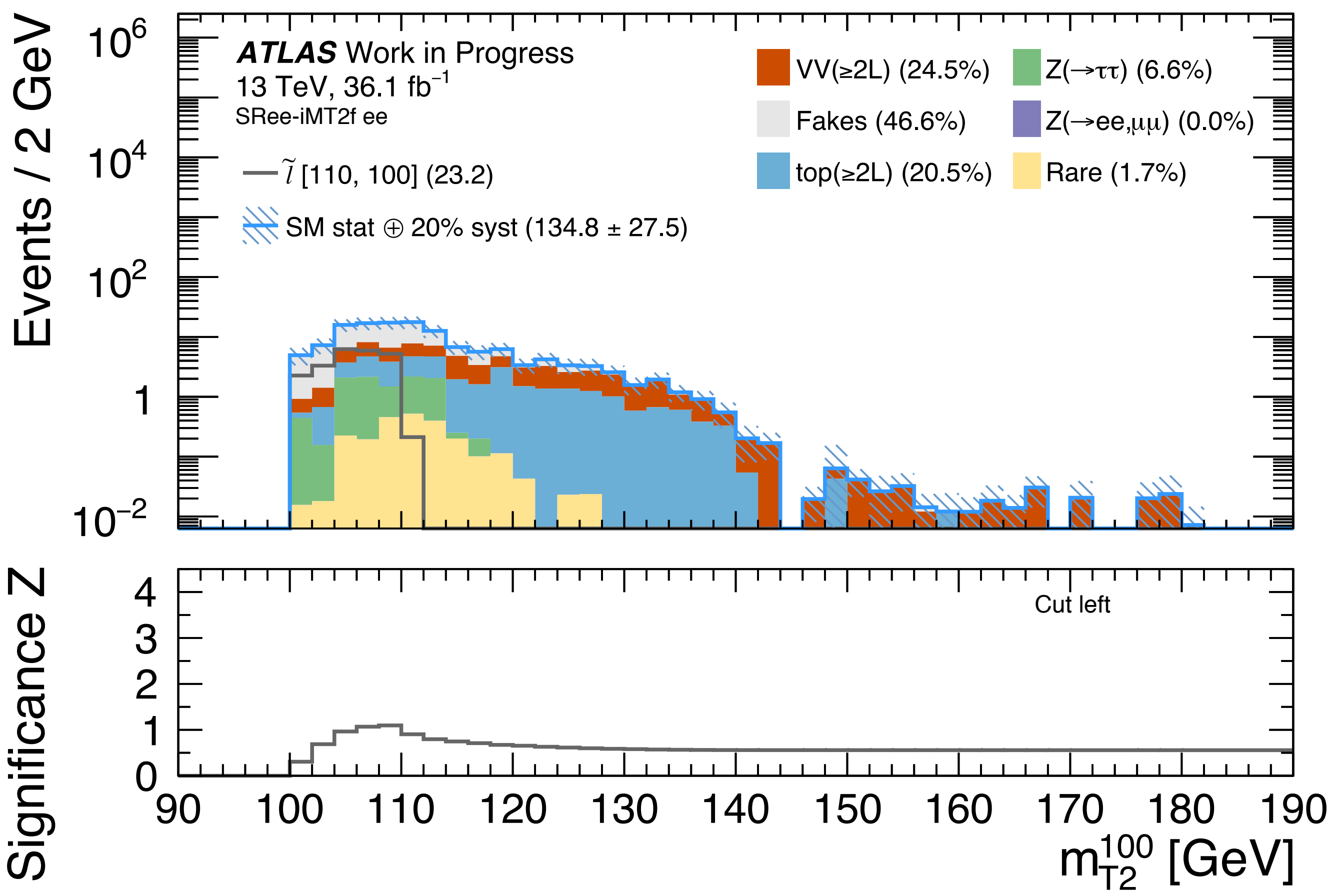


μμ channel

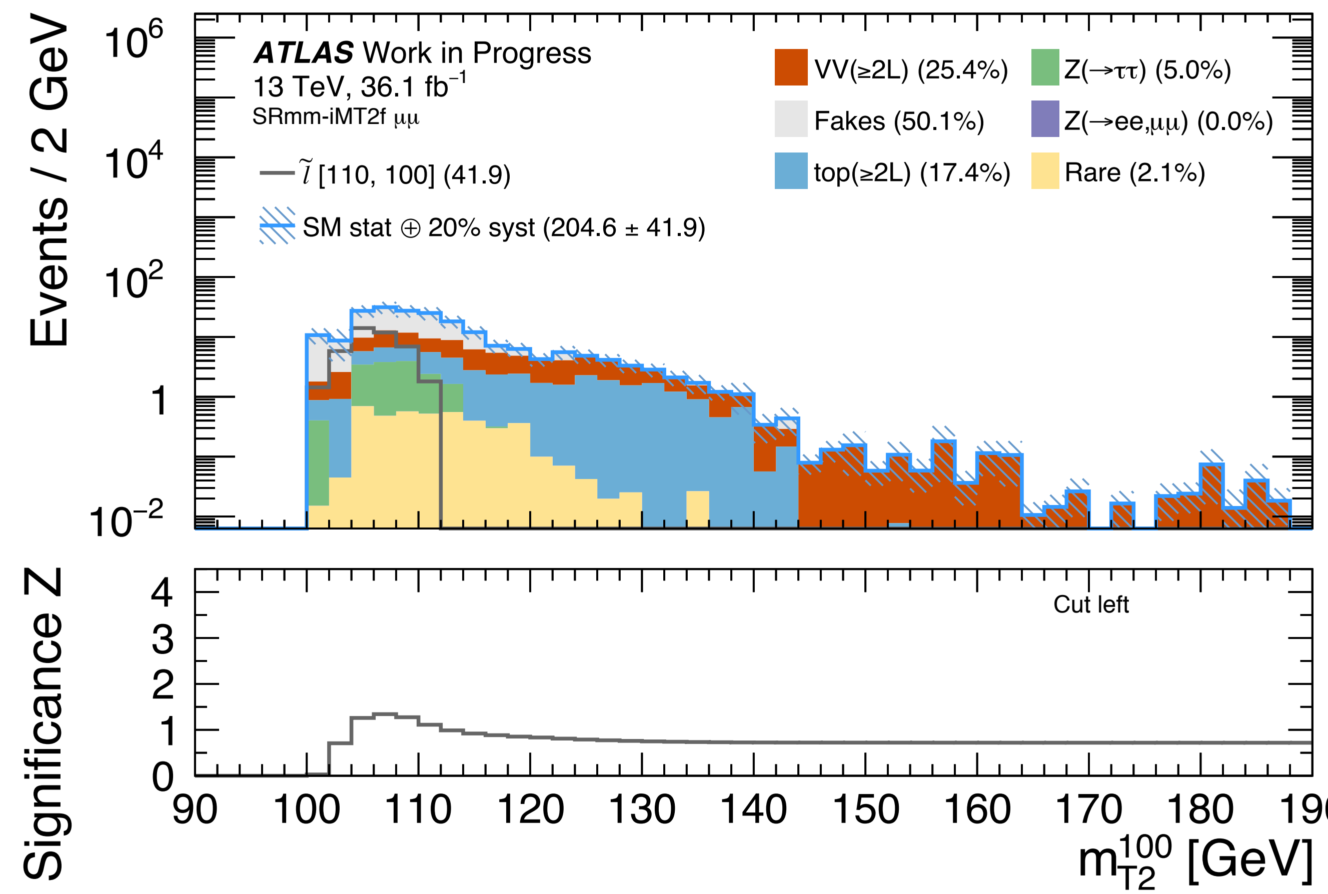


Slepton SR for ee vs. μμ

ee channel



μμ channel



Fitting Strategy

Higgsino SR

Variable	Selections optimised for Higgsinos						
$E_T^{miss}/H_T^{leptons}$	$> \text{Max}\,(5.0, 15 - 2 \cdot m_{\ell\ell}/\text{ GeV})$						
$\Delta R_{\ell\ell}$	< 2.0						
$m_T^{\ell_1}$	< 70 GeV						
SRee-, SRmm-	eMLLa	eMLLb	eMLLc	eMLLd	eMLLe	eMLLf	eMLLg
$m_{\ell\ell}$ [GeV]	[1, 3]	[3.2, 5]	[5, 10]	[10, 20]	[20, 30]	[30, 40]	[40, 60]
SRSF-	iMLLa	iMLLb	iMLLc	iMLLd	iMLLe	iMLLf	iMLLg
$m_{\ell\ell}$ [GeV]	< 3	< 5	< 10	< 20	< 30	< 40	< 60

Slepton SR

Variable	Selections optimised for sleptons					
$E_T^{miss}/H_T^{leptons}$	$> \text{Max}\left(3.0, 15 - 2 \cdot \left[m_{T2}^{100}/\text{ GeV} - 100\right]\right)$					
SRee-, SRmm-	eMT2a	eMT2b	eMT2c	eMT2d	eMT2e	eMT2f
m_{T2}^{100} [GeV]	[100, 102]	[102, 105]	[105, 110]	[110, 120]	[120, 130]	≥ 130
SRSF-	iMT2a	iMT2b	iMT2c	iMT2d	iMT2e	iMT2f
m_{T2}^{100} [GeV]	< 102	< 105	< 110	< 120	< 130	≥ 100

General strategy: bin in inclusive and exclusive SRs for shape fit (separately for ee and μμ in the exclusive fits)

Higgsino: exploit kinematic endpoint in mll, using leptons with small ΔR

Slepton: use m_{T2} with a 100 GeV neutralino assumption

Yield Summary